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EXPERIMENTAL STUDY ON NUCLEATE BOILING OF WATER IN VERTICAL UPFLOW AND DOWNFLOW

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Abstract—An experimental study on nucleate boiling of water was carried out using an annular vertical channel both in upflow and downflow. Heat transfer data are given in different conditions of subcooling and fluid velocity. Photographs show different behaviour of heat transfer mechanism.

1. INTRODUCTION

The design of modern heat transfer equipment needs a better knowledge of the transfer mechanism in order to improve thermal performance.

The calculation methods employed when designing boiling equipment make use of simplified relations to predict the heat transfer coefficients. These procedures are essentially conservative in most cases and lead to oversized heat transfer surfaces. The boiling heat transfer mechanism is very complex and there are no relations available of general validity. On the other hand, most experiments in the past, dealt with boiling on single tubes in horizontal or vertical upflow and the problem was how to relate these experimental results with a more complex geometry. Taborek (1974) carried out experiments on tubes bundles only in recent years.

Other aspects of the boiling process need further detailed investigations, such as those regarding the influence of the flow direction on heat transfer coefficient during fully and partial nucleate boiling.

It is generally known that the bubble diameter on detachment depends on three distinct forces: buoyancy, drag and surface tension as pointed out from Levy (1967) and from Abdelmessih *et al.* (1972). As a consequence bubble diameters are generally smaller in upflow than in downflow.

Chen & Chuang (1979) studied the effect of surface orientation on bubble frequencies in nucleate pool boiling of R 11, and they proved that the bubble frequencies strongly increase by increasing the orientation angle.

Simoneau & Simon (1966), studying boiling nitrogen with upward and downward flow, observed higher accumulation of void in downward flow.

The above mentioned aspects of the nucleate boiling process lead to suppose that different heat transfer coefficients may occur in vertical upflow or downflow.

The influence of flow direction on heat transfer coefficient in nucleate boiling has not been systematically studied.

The aim of this paper is to provide experimental data on nucleate boiling in vertical annular channel with different subcooling and inlet velocity.

2. TEST FACILITIES

The experimental apparatus used in the present work, and described in a previous paper by Bartolini *et al.* (1978), is schematically shown in figure 1. It consists of a demineralized water loop with a pump *C*, an electrical heater *R*, a test section *P*, a flow meter *D*, a heat exchanger *S*, a flow regulating valve *M* and a condenser *N*. Three resistance thermometers T_1, T_2 and T_3 allow the flow rate cooling water to heat exchanger *S* and the power supplied to the electrical heater *R* to be controlled.

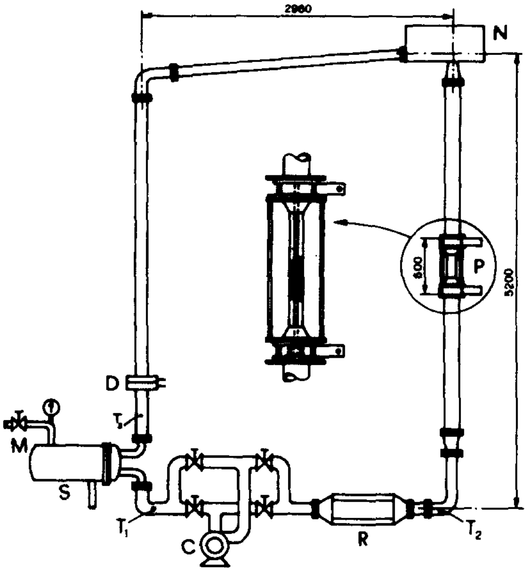


Figure 1. Experimental apparatus.

Through a system of valves the flow direction is changed thus obtaining a vertical upflow or downflow. The annular test section, vertically placed, consists of an AISI 304 stainless steel tube 600 mm in length, 10 mm o.d. and 1 mm thick, centered inside a 49 mm Pyrex tube.

The surface temperature was measured with eight 28 AWG thermocouples placed at equal distance from the mid section and 100 mm apart, welded to the inner surface of the tube. The corresponding outside surface temperature was evaluated taking into account a correction factor.

The specimen was electrically heated by means of a low voltage D.C. power supply. The heat flux was evaluated by voltage and current measurements.

The inlet bulk temperature was measured by means of two thermocouples placed in the liquid 500 mm apart from the specimen in both flow directions.

3. EXPERIMENTAL RESULTS

Boiling tests were carried out with demineralized water at 1.2 bar pressure for different values of mean velocity and inlet fluid temperature. The velocities ranged up to 0.8 m/s, the subcooling between 10 and 45°C and specific heat flux up to $80 \cdot 10^4$ W/m^2. Data was taken with increasing heat flux after waiting about 15 min. to obtain steady state conditions.

Further pool boiling tests were carried out using the same test section, vertically placed in a vessel.

Figure 2 shows some experimental results obtained during upflow and downflow with mean velocity 0.2 and 0.8 m/s at three different degrees of subcooling. The dashed line refers to the saturated pool boiling data obtained with the same heating element. The comparison between the results obtained under the two different experimental conditions shows almost the same heat transfer coefficients when the fully developed nucleate boiling occurs.

The different flow direction has not modified considerably the heat transfer coefficient values during fully developed nucleate boiling. Different values have instead been observed for the highest subcooling and at the lowest velocity values, in the regime of single phase forced convection and partial nucleate boiling. This depends on the different influence exerted by the natural convection on the hydrodynamic conditions occurring along the tests section for the two flow directions.

Referring to the transition region from forced convection to the nucleate boiling, the

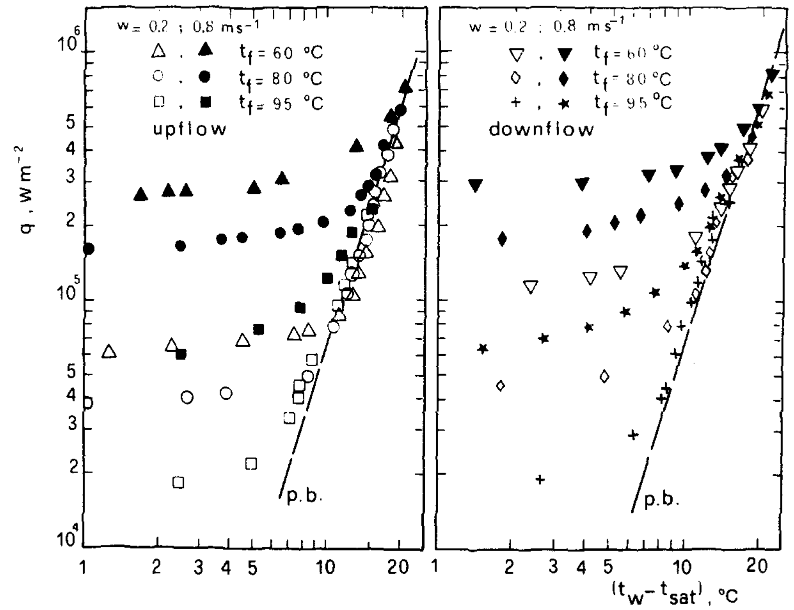


Figure 2. Experimental data for upward and downward fluid flow.

experimental data can be related by means of interpolation equations proposed by different authors.

In this paper it has been considered the Kutateladze's (1961) equation:

$$\frac{h}{h_f}=\left[1+\left(\frac{h_b}{h_f}\right)^n\right]^{1/n} \qquad [1]$$

where h_f and h_b are the heat transfer coefficients during single phase forced convection and during developed nucleate pool boiling, respectively.

The diagram of figure 3 gives the data obtained by using the above mentioned equation where exponent $n = 5.5$, as suggested by Guglielmini & Nannei (1980). The h_f values were assumed to be equal to the experimental data for each test condition and the h_b values equal to the $q/(t_{w,b} - t_f)$ ratio, where $t_{w,b}$ is the wall temperature taken from saturated pool boiling data at the effective heat flux q.

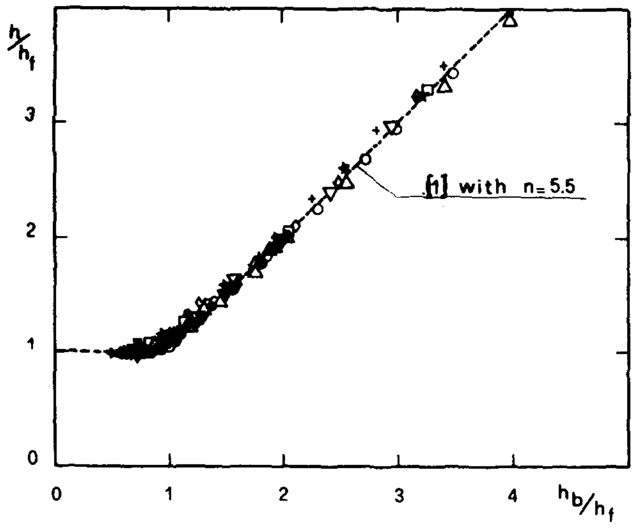


Figure 3. Comparison of [1] with experimental data.

Finally, it is interesting to note that the h_f values obtained concern the combined free and forced convection in the transition region from laminar to turbulent flow. In this region, particularly for downflow, it has not been possible to compare our experimental data with the correlations reported in the available literature, because data are still insufficient in this field.

4. DISCUSSION AND CONCLUSIONS

The experimental results obtained show that the heat transfer coefficient during nucleate boiling does not depend on flow direction at the different velocities and degree of subcooling considered.

Figure 2 shows indeed that, for both flow directions, the heat transfer coefficient during fully developed nucleate boiling is close to that observed in pool boiling, Moreover the relation proposed by Kutateladze (1961) can be used for partial nucleate boiling in upflow and downflow (see figure 3).

During the tests a photographic investigation was carried out in order to examine the hydrodynamics of the two-phase flow under the two conditions studied for a better understanding of the phenomenological aspects of the heat transfer process in connection with the studies of Al-Hayes & Winterton (1981) and of Chen & Chuang (1979).

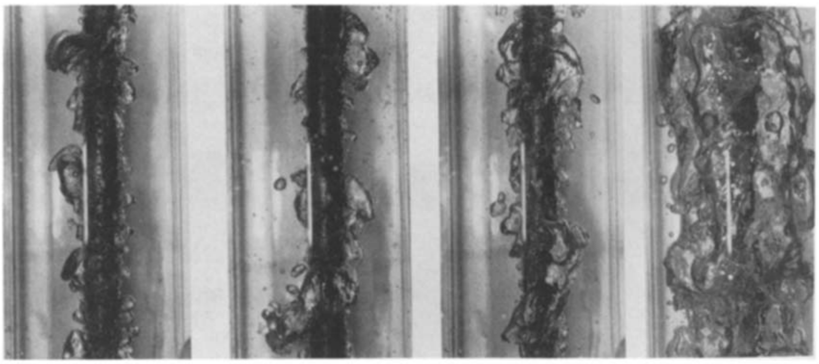
As can be seen in figures 4(a) and (b), the photographs show a similar boiling characteristics and local void accumulation in both upflow and downflow at the highest mean velocity values.

Higher values of the void accumulation (see figures 4(c) and (d)) occur in the test section when; in the downflow, the fluid velocity reaches values near to those typical of the bubble rise velocity in a liquid pool. In this condition the bubble diameter on detachment is higher than that occurring during the upflow boiling, owing to the fact that in downflow the buoyancy forces in the bubbles are exerted in the opposite direction of the fluid flow.

In order to explain the equivalence between the heat transfer coefficient in the two flow directions it can be assumed that other parameters, characteristic of boiling regime may change simultaneously with the bubble diameter on detachment.

The photographs taken with stroboscopic technique during boiling at low velocities show indeed a higher frequency of vapour bubble formation in upflow as compared to downflow. This effect looks like that found by Chen & Chuang (1979) who observed a strong effect of the boiling surface orientation on the bubble frequency.

This phenomenon requires more thorough analysis and other tests on typical parameter of the boiling process are being carried out.



(a) (b) (c) (d)

Figure 4. Comparison of nucleate boiling in upflow and downflow ($q = 40 \times 10^4$ W/m^2; $t_f = 95°$C). (a) up $W = 0.8$ m/s. (b) down $W = 0.8$ m/s. (c) up $W = 0.2$ m/s. (d) down $W = 0.2$ m/s.

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